CHAPTER 3

ENERGY CONSUMPTION AND ENERGY SOURCES ON PLANET EARTH

3.1. DEFINITION OF ENERGY AND UNITS FOR ENERGY AND POWER

As taught in every highschool, it takes kinetic energy for anything to move. This movement energy can be obtained by conversion of stored-up (potential) energy that is released. Without energy and energy conversions, the whole Universe would be dead and we would not exist. Since we will be discussing energy usage, energy exchanges, and energy supplies, it is necessary we define a unit of energy. For example how many units of energy are in a liter or gallon of petrol.

The word ‘energy’ comes from the Greek meaning ‘inherent work’. Although others before him had hinted at the conservation of mechanical work and heat, it was Sir James Prescott Joule (1818–1889) who first carefully measured and proved the inter-convertability of heat and mechanical work, firmly establishing the abstract concept of energy and conservation of energy. He showed that a certain amount of mechanical motion energy could be produced by a certain amount of heat energy. Also that a big car needs more energy to be moved than a small car, in proportion to its weight.

The laws of energy conservation and energy exchange are the cornerstones of physics. One can define energy on the microscopic as well as macroscopic scale. Microscopic atoms, molecules, electrons, protons, neutrons, nuclei, photons, etc. are all endowed with energy, in addition to mass, charge, etc. Likewise cars and trucks moving over a highway possess kinetic energy, acquired by converting petrol-fueled heat of combustion in their engines into mechanical motion of their wheels and thence onto their vehicle. People who drive cars can visualize energy best by equating it with liters or gallons of petrol. They know their car needs 60 liters or 16 gallons of petrol to fill their tank that allows them to drive 600 km or 373 miles. In technical parlance, the chemical energy contained in 60 liters (16 gallons) of petrol when liberated as heat of combustion, is converted by the engine to mechanical

energy of wheel rotation, taking the car a distance of 600 km (373 miles). Thus one can equate 1 liter of petrol energy with 10 kilometers of mechanical work, or 1 gallon with 23 miles.

Energy can be in the form of kinetic energy (e.g. a falling stone) or potential energy (e.g. a stone on the edge of a cliff ready to fall), one being convertible into the other. Chemical energy stored in molecules like petrol, and nuclear energy present in atomic nuclei, are both forms of potential energy that can be converted into kinetic energy under certain conditions. Heat is the total kinetic energy from swarms of chaotically moving or vibrating molecules or atoms. Heated molecules in a gas can be directed to push a piston, thereby converting heat into mechanical energy of motion. When hydro-carbon (C_mH_n) molecules in petrol react with heated atmospheric oxygen (O_2) in a combustion engine, C, H, and O atoms are rearranged into new molecular compounds (CO_2 and H_2O) with liberation of kinetic energy in the form of heated gases that move pistons. Similarly a neutron flying into the nucleus of a uranium atom, can cause a re-arrangement of protons and neutrons in the nucleus (Chapters 5 and 6). This results in the splitting (fissioning) of a uranium nucleus into two halves and liberation of kinetic energy imparted to the two recoiling fission fragments which generate heat in the solid that embeds them. The amount of energy liberated in the fission of a nucleus is generally ten million times larger than that liberated in a chemical reaction. This is the reason why a nuclear plant can produce so much more power from a kilogram of nuclear fuel (uranium), than a coal- or oil-fired power plant can generate from a kilogram of petro-chemical fuel.

The physicist's unit of energy is aptly called the Joule (abbreviated J). Power is defined as the energy delivered per unit time or the energy *rate*. In physics, the standard unit of power is the Watt (W) or Joule per second (J/s). That is, $1\ \mathrm{W} = 1\,\mathrm{J/s}$. Comparing energy with a cup of water, then power is like cups of water pouring out of a faucet per unit time. The antiquated 'horsepower' (HP) unit, based on the strength of horses, is still used to rate car engines. It equals 746 Watt, that is $1\,\mathrm{HP} = 746\,\mathrm{W} = 746$ Joules per second. Historic definitions of various other units for energy and power can be found in physics textbooks. For example the calorie energy unit which is still used, is based on heating 1 gram of water by 1 degree centigrade (Celsius), and equals 4.2 Joules ($1\,\mathrm{cal} = 4.2\,\mathrm{J}$). For multiples of a basic unit, one uses k for kilo (thousand or 10^3), M for mega (million or 10^6), G for giga (billion or 10^9), and T for tera (trillion or 10^{12}). Thus 1 kW equals one thousand Watts of power, 1 MW is one million Watts of power, etc. A peculiar energy unit is the kWh or kilowatt-hour which is disguised as if it is a power unit. It actually is an energy unit and represents energy delivered at a rate of $1000\,\mathrm{Watts} = 1000\,\mathrm{Joules/second}$ for a period of $1\,\mathrm{hour} = 3600\,\mathrm{seconds}$. Thus $1\,\mathrm{kWh} = 1000(\mathrm{J/second}) \times 3600\ (\mathrm{seconds/hour}) = 3.6\,\mathrm{million\ J} = 3.6\,\mathrm{MJ}$.

In dealing with large quantities of energy, we shall use three units, the Giga-Joule = 1 GJ = 1 Billion Joule; the MegaWatt-hour = 1 MWh = 1 Million Watts

for One Hour; and the MBTU = 1 Million BTU (British Thermal Unit). They are related as shown in Brief 1[2]. Conversion factors are needed so that one can compare reported data from different energy sources which use different units. In comparing amounts of energy generated from a kilogram of oil, coal, or uranium, it is also important to specify whether the energy is in the form of heat, electricity, or mechanical motion. We follow the convention of placing (e) or (m) in parentheses after units of energy for the latter two; otherwise it is assumed to be heat. Thus 1 GJ(e) designates electric energy, while 1 GJ is a quantity of heat. The distinction is important because electrical and mechanical energy are of a higher grade.

Most of man's energy usage involves mechanical motion or electricity, obtained by conversion of heat energy via a steam or gas turbine, or by direct electrochemical energy conversion to electricity. Physics shows that usually only 30% to 40% of heat (= chaotic molecular motion) can be converted by a turbine into macroscopic mechanical motion or electricity[3]. The balance is dumped as low-temperature heat into the air or coolant (lake or ocean water). Direct conversion of chemical energy into electricity (fuel cells) and mechanical motion is more efficient, and can take place with (practical) efficiencies of 45% to 85%. In evaluating world energy resources, fuels are measured by mass (volume and density) whose energy content is given as latent heats of combustion, while hydro, wind, or solar sources specify electric outputs. In comparing these energy forms, we shall assume a coarse conversion factor of 33% for conversion of heat into electricity. For electrochemical conversions we shall assume efficiencies of 55%, while for interconversions of mechanical and electric energy we assume $\sim 100\%$ (Brief 1).

It is helpful to recall here that a tankful of petrol in a medium-sized automobile contains about 60 liters (16 US gallons). This contains 2.2 GJ of chemical combustion energy which can be converted to mechanical motion to propel the car a distance of approximately 600 km (373 miles). Conversely 1 GJ of heat energy is stored in 27 liters (7.3 gallons) of petrol which moves a car 273 km (170 mi).

Brief 1 lists the approximate equivalences for automobile propulsion and travel using petrol, ammonia, and hydrogen fuels. Heat of combustion in an ICE is assumed to be convertable to mechanical energy by a factor of 0.33, while the efficiencies of FCEs are assumed to be 0.55. Ammonia and/or hydrogen may become the main fuel of the future for automotive fuel-cells (Chapter 4).

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[2] We shall use the word 'brief' for any table, chart, sketch, or figure that summarizes or illustrates a concept or relationship.

[3] The 'second law of thermodynamics' states that the maximum mechanical energy extractable from heat is given by the Carnot fraction $(T_1 - T_2)/T_1$, where T_1 and T_2 are inlet and outlet turbine/engine temperatures.

BRIEF 1: ENERGY AND POWER UNITS AND CONVERSION FACTORS

ENERGY

$$1\ \text{GJ} = 10^9\ \text{J} = 0.278\ \text{MWh} = 278\ \text{kWh} = 9.48 \times 10^5\text{BTU} = 0.948\ \text{MBTU}$$

$$1\ \text{MWh} = 1000\ \text{kWh} = 3.6\ \text{GJ} = 3.413 \times 10^6\ \text{BTU} = 3.413\ \text{MBTU}$$

$$1\ \text{MBTU} = 10^6\ \text{BTU} = 1.055\ \text{GJ} = 0.293\ \text{MWh} = 293\ \text{kWh}$$

POWER:

$$1\ \text{GJ/y} = 31.71\ \text{J/s} = 31.71\ \text{W} = 0.03171\ \text{kW}$$

$$1\ \text{W} = 1\ \text{J/s} = 3.6\ \text{kJ/h} = 31.54\ \text{MJ/y}(1\ \text{y} = 3.154 \times 10^7 s)$$

$$1\ \text{kW} = 1\ \text{kJ/s} = 3.6\ \text{MJ/h} = 31.54\ \text{GJ/y}$$

HEAT → ELECTRICITY OR MECHANICAL ENERGY:

$$3\ \text{GJ} \rightarrow 1\ \text{GJ(e, m)};\ 3\ \text{MWh} \rightarrow 1\ \text{MWh(e, m)};\ 3\ \text{MBTU} \rightarrow 1\ \text{MBTU(e, m)}$$

EQUIVALENCES FOR INTERNAL COMBUSTION ENGINES (ICE):

One 'tankful' petrol $\approx$ 45 kg petrol $\approx$ 60 liters(16 gal)of petrol

$\approx$ 2.2 GJ $\rightarrow$ 0.72 GJ(m) $\rightarrow \sim$ 600 km(373 mi)of car travel

One 'tankful' ammonia $\approx$ 47 kgNH_3 $\approx$ 40 liters(11 gal) of liquid ammonia @ 20 atm

$\approx$ 2.2 GJ $\rightarrow$ 0.72 GJ(m) $\rightarrow \sim$ 600 km(373 mi) of car travel

EQUIVALENCES FOR FUEL CELL ENGINES (FCE):

One 'tankful' hydrogen $\approx$ 10 kgH_2 $\approx$ 600 liters(160 gal) hydrogen gas @ 245 atm

$\approx$ 1.3 GJ $\rightarrow$ 0.72 GJ(e, m) $\rightarrow \sim$ 600 km(373 mi) of car travel

One 'tankful' ammonia $\approx$ 28 kgNH_3 $\approx$ 24 liters(6.5 gal) of liquid ammonia @ 20 atm

$\approx$ 1.3 GJ $\rightarrow$ 0.72 GJ(e, m) $\rightarrow \sim$ 600 km(373 mi) of car travel

3.2. AMOUNTS AND FORMS OF ENERGY CONSUMED BY MAN

According to statistics supplied by the US Census Bureau and Department of Energy (DOE), there were 281,422,000 people living in the USA in 2000, who consumed a total of 1.18×10^{11} GJ/y of heat-equivalent energy from the primary energy sources listed in Brief 2A. The U.S. consumption rate was thus 419 GJ/y or 4.4 kW(e) per person. This compares with a total world consumption of 4.01×10^{11} GJ/y of

heat energy by 6,157,401,000 people, or 67 GJ/y (0.71 kW(e)) per person. These per-capita consumption figures might indicate that a US resident is consuming 6 times the world average. However a lot of hardware in the world (cars, planes, ships, bridges, tractors, etc.) used in non-US countries were fabricated in the USA, so some of the energy for their manufacture must be allocated to non-US residents. This increases the 67 GJ/y figure and decreases the US figure of 419 GJ/y. These considerations apply primarily to Asia, Africa, and South-America who buy such hardware in exchange for labor-intensive (non-petrol-consuming) goods, oil, and raw materials. Europe and Japan, like the USA, also make energy-consuming hardware products traded throughout the world. Without considering detailed balances of world trade and energy exchanges, coarse estimates change the above figures to about 73 GJ/y or 0.77 kW(e) per person for the world and about 300 GJ/y or 3.2 kW(e) per US citizen, still four times the world average.

In the next 20 years, one can expect non-USA energy consumption to increase, particularly in China. The world consumption rate is estimated to increase to $123\,\mathrm{GJ/y} = 3.9\,\mathrm{kW} = 1.3\,\mathrm{kW(e)}$ per person when averaged over the years between 2005 and 2025. With a world population of 6.1 billion in 2000 leveling to 7.8 billion predicted for 2025, these figures forecast a world energy consumption rate of about 0.86 trillion (10^{12}) GJ per year averaged over the next 20 years. With total primary energy reserves as listed in Brief 2B, one then calculates depletion times of 16.4 years for oil, 18.4 years for natural gas, 153 years for coal, and 1100 years for uranium, *assuming* all needed heat-equivalent energy is supplied *only* by oil, or *only* by natgas,[4] or *only* by coal, or *only* by uranium. Exploitation of 1.5 trillion barrels of oil from shale and tar-sands, and 10 quadrillion cubic feet of natgas

BRIEF 2A: ANNUAL ENERGY RESOURCE CONSUMPTION IN THE USA (2000)

Energy Resource	Annual Quantity Consumed	Equivalent Heat Consumption	Percentage
Oil	7.08×10^9 barrels/y	4.0×10^{10} GJ/y	33.90%
Natgas (Natural Gas)	2.38×10^{13} cu.ft/y	2.5×10^{10} GJ/y	21.18%
Coal	1.70×10^9 tons/y	3.74×10^{10} GJ/y	31.68%
Uranium$^{1)}$	20,000 tons/y$^{1)}$	0.85×10^{10} GJ/y$^{1)}$	7.20%
Hydroelectric$^{2)}$		0.33×10^{10} GJ/y	2.80%
Geothermal$^{2)}$		0.034×10^{10} GJ/y	0.28%
Wood/Bio, Wind, Solar$^{3)}$		0.35×10^{10} GJ/y	2.96%
TOTAL:		11.80×10^{10} GJ/y	100%

NOTES: $^{1)}$ With present U-235 'burners', only 0.5% of the intrinsic uranium energy is utilized. With U-238 breeder reactors, only 100 tons/y would be needed to provide 0.85×10^{10} GJ/y; $^{2)}$ Hydro and Geothermal are close to the maximum available in the USA; $^{3)}$ Wind and Solar may expand three-fold in the next twenty years but most likely can never provide more than ten percent of total energy needs.

[4] We shall abbreviate 'natgas' for natural gas (mix of methane, ethane, propane, butane) from here on.

BRIEF 2B: PRESENT (2004) WORLD RESERVES OF PRIME ENERGY RESOURCES				
Resource	Quantity	Heat Content	Conversion Factor	Depletion Time @ 123 GJ/y per man (Popul'n $= 7 \times 10^9$)
Oil (including tarsands)	2.5×10^{12} barrels	1.41×10^{13} GJ	5.65 GJ/barrel	16.4 years
Natgas (including sea-beds)	1.5×10^{16} cu.ft	1.58×10^{13} GJ	1.05 GJ per 1000 cu.ft	18.4 years
Coal	6×10^{12} tons	1.32×10^{14} GJ	22 GJ/ton	153 years
Uranium	1.1×10^7 tons	8.60×10^{14} GJ ($^{235}U + ^{239}Pu$)	8.6×10^7 GJ/ton	1100 years
Thorium	3×10^6 tons	2.87×10^{14} GJ (^{233}U)	8.6×10^7 GJ/ton	333 years
TOTAL:		9.63×10^{14} GJ		

NOTES: Depletion times assume all mankind's energy needs are provided by one resource only. 1 barrel = 42 gallons = 159 liters; 1 gallon = 3.785 liter; 1cuft = 28,316 cm^3 = 28.316 liters; 1 ft = 30.48 cm; 1 mile = 1.609 km; 1 lbs = 0.454 kg; 1 ton = 2000 lbs = 907.19 kg; 1 tonne = 1000 kg = 2204.62 lbs; 1 year = 365 days = 8,760 hours = 525,600 min = 3.154×10^7 sec.

from sea-beds, requiring less than 20% of contained fuel energy for recovery, are included. If tar-sand oil and sea-bed natgas are excluded, only 1 trillion barrels of oil and 5 quadrillion cubic feet of natgas are left, and depletion periods change to 7 years for oil and 6.5 years for natgas. Of course it is unrealistic to assume that *only* oil, *only* natgas, *only* coal, or *only* uranium will be used to support *all* of man's energy needs. Nevertheless these depletion periods are useful to indicate the relative mortality of these resources, and to show uranium's superior long life.

In the real world, the transportation sector which comprises our vast fleets of land, air, and sea vehicles, consume most of the available oil. In the USA, about 35% of all energy is consumed by transport vehicles, but world-wide this percentage is closer to 40% (the balance of 60% is mostly electricity), since less energy for heavy industry is used. At 3.44×10^{11} GJ/y, the actual availabilty of petrol beyond the year 2005 would then be 24 years without tar-sands oil, and 41 years with tar-sands oil included.

While locomotion of most transportation vehicles is obtained via petrol-burning combustion engines, electricity is generated by means of steam or gas turbines that utilize heat obtained from coal, uranium, or natgas. Additional small quantities of electric energy are provided by geothermal sources, hydroturbines, windturbines, and solar cells. To prolong the epoch of the well-developed combustion engine, natgas can be compressed (at about 120 atm) and used in place of petrol. In The Netherlands where the price of petrol is four times higher than in the USA, many automobilists used cylinders of compressed natgas instead of petrol in the 1970's when natgas was less expensive. That is, compressed natgas can be substituted for petrol to propel automobiles when oil becomes scarce and

expensive. For this reason, it would be prudent to preserve natgas for future use as a portable fuel and not waste it now in elecric power generation, which can easily be run on coal and uranium alone. If we assume that all of the presently available 5 quadrillion cubic feet of natgas (*not* including speculative retrieval of methane-hydrate from sea-beds) will be available for fueling our transport vehicles, in addition to the 2.5 trillion barrels of oil (including tar-sands oil), the period for continued use of the well-developed combustion engine might be extended. Instead of 41 years, it then would take 56 years to petro-fuel exhaustion. This is with the proviso that oil and natgas are used *only* for vehicle fuels, and electricity is produced *only* by coal, uranium, and renewables. Under this scenario, more time is available to develop new propulsion systems and synfuels for aircraft, ships, and land transport. Many believe the above time estimates are too optimistic and that the most-probable out-of-oil and -natgas time-point will be reached in 40 years.

If the burning of coal in electric power plants is halted to reduce global warming and to use/conserve it as a raw material for making plastics,[5] one finds that present nuclear power generation must be expanded sixfold to replace all coal power plants presently used for making electricity. For the USA, this means that five-hundred uranium-burning plants must be added to the existing one hundred operating nuclear power plants. However a further expansion of uranium power plants from five hundred to one thousand units of 1200 MW(e) each must be in place to accomodate the manufacture of portable fuels with nuclear electricity or heat for new vehicle propulsion systems that can no longer depend on petrol or natgas. Severe oil shortages will develop well before the nominal 40-year total depletion period is reached, as production from different oil fields are reduced or stopped (prices increased!) when they approach exhaustion. It is estimated this will happen in about 25 years. Though it is impossible to set a precise date, we believe *we will see few petrol-driven cars after 2030*. As indicated in Brief 2, electricity from 'renewables' (hydro, wood/biomass, geothermal, wind, solar) helps. But for them to produce enough portable synfuels for all the world's vast transportation fleets is virtually impossible (Subchapter 3.3).

In the manufacture of portable synfuels there are losses in converting prime heat or electricity into chemical energy of a synfuel. As shown in Chapter 4, synthesizing hydrogen, ammonia, or hydrazine from air and water actually can be done only with an efficiency between 10% and 60%. That is, 40% to 90% of prime energy is lost in converting it into portable synfuel energy. As long as there is an abundant source of prime uranium (or coal) energy, this poses no problem. Even if it would take 3 GJ of prime energy to make 1 GJ of synfuel energy, there is no bottleneck. To a traveling automobilist, portable synfuel energy is more valuable than non-portable nuclear reactor heat. He does not mind if a substantial amount of the original nuclear

[5] The word 'plastics' is used here to include carbon nanotubes, fibers, and most materials and products presently derived from petrochemicals.

heat used for chemical synthesis is lost, just like he is quite willing to waste 66% of the heat produced in his internal combustion engine as long as the balance of 33% is converted to move his vehicle. On the other hand if the only source of prime energy is biomass-generated alcohol, and it takes more alcohol fuel to grow alcohol fuel (due to running of farm equipment, distillation process, etc), the situation would be unsustainable in a no-oil, no-coal, no-uranium future. Only with uranium-generated electricity or heat to provide the energy needed for cultivation of plants and to extract their alcohol, can bio-alcohol be a practicl synfuel, converting non-portable nuclear energy into a portable fuel.

Electricity is one of the greatest gifts to mankind allowing him to communicate by telephone, radio, television, and to have all the comforts of the modern home such as electric lighting, air-conditioning, refrigerators, heating, cooking, etc. Without electricity we would have candles and torches for lighting, cold water for bathing, spoiling food, and sweltering dwellings in summer. Instant communications around the world would also be impossible. It is very fortunate that nature has provided us with very light negative electrons that can pass swiftly through metal conductors such as copper. If electrons would have been heavy (with the same mass as positive protons), there never could have been readily available inexpensive electricity as we know it. Because of the properties of electrons, electric power can be delivered rapidly and distributed widely with little propagation loss, to the great benefit of man. The same comment applies to uranium fission which allows the entire world to have at least a thousand years of electric energy. In the early days of electric power, protesters tried to block its distribution, claiming that thousands of people would die if high-voltage AC power lines would be stretched out over the land. Similar preposterous assumptions are made by today's anti-nuclear lobbyists who try to impede expansion of nuclear power. Senator Robert Kennedy once observed that in almost every national issue 'One-fifth of the people are always against,' and that the contrarians are quite bull-headed. Philosophically one can argue whether electricity and nuclear power are a blessing or curse to man. It is up to man to use these gifts of nature for good or evil. One hopes destructive uses can be rooted out and all of mankind will band together to enjoy the benefits of ample uranium-generated electricity for millennia.

3.3. LIMITATIONS OF 'RENEWABLE ENERGY'

Recently there have been assertions that nuclear energy is not needed and that all oil-derived petrols can be replaced by 'renewable' bio-mass fuels such as corn-derived alcohol, bio-diesel, bio-hydrogen, etc. We shall examine this proposition now in some detail. As discussed, the estimated world-averaged energy consumption rate between 2005 and 2025 will be about 1.3 kW of equivalent electric energy per person, or 9.1 billion kW for 7 billion people[6]. A typical 100-Watt lightbulb, when

[6] In this Subchapter, we shall omit (e) in kW(e) for brevity.

turned on, continuously burns 100 Joules of electric energy per second. If in the next two decades each person consumes 1.3 kW of energy on average, he/she would continuously burn the equivalent of 13 electric lightbulbs. This energy consumption rate includes each person's share of oil and electricity used in making foods and goods and their transport to market, for fuel to drive to work and back, for making steel and aluminum used in cars, bridges, buildings, ships, airplanes, appliances, and for home lighting, cooking, heating, cooling, etc. The world-average figure of 1.3 kW per person (presently 0.77 kW) assumes that standards of living in China, India, Indonesia, and other countries will improve in the next decades. Also it is assumed that reasonable conservation will be practiced and excessive energy is not wasted in too many global scorched-earth wars.

Solar radiation at the earth surface amounts to about 1.35 kW per square meter or 5,463 kW per acre when sun-shine peaks. The overall efficiency of plants or trees to convert earth-incident solar energy into burnable carbonaceous chemical energy (alcohols, wood, etc) is about 0.03% for the best bio-fuel producers [Refs. 48, 49]. This includes average diurnal, seasonal, and weather effects, as well as foliage intercept fractions, crop turn-over times, and plant photosynthesis efficiencies (plants use a lot of captured solar energy for pumping water). With 5,463 kW per acre of peak solar irradiation, plants might thus produce 1.6 kW per acre of potential bio-fuel. Assuming 10% for access roads to cultivate and harvest, one acre could yield 1.5 kW of bio-fuel energy, if crops are continuously replanted after harvesting. We are talking here about a continuous balance between solar energy delivery, conversion, and harvesting of bio-energy. One can accumulate bio-energy for years by growing timber for example, and consume it all in a few hours at a thousand kW (a million Joules per second) per acre in a forest fire. But it takes a long time for re-growth before a repeat of such a high energy release rate is possible. Because of energy conservation (what goes out must come in), one can only extract 1.6 kW per acre of year-averaged bio-fuel energy. The fossil fuels we burn up today in one year, were deposited by plants over millions of years in the past.

To replace all the world's petro-fuel and electric energy with synfuels and electricity derived *only* from bio-mass, will take about (9.1 billion kW)/(1.5 kW/acre) = 6 billion acres of arable land. To grow, harvest, and process bio-crops, one needs tractors, fertilizers, processing operations, etc., which all consume energy. Proponents of biofuel production claim this takes less than 90% of the alcohol energy produced by corn crops for example. Assuming that improvements can lower this number to 80%, bio-fuel production would need five times more land, or 30 billion acres to generate a net of 9.1 billion kW of marketable portable bio-fuel. Since the world's total arable land is about 8 billion acres, this is four times more than what is available. The total surface area of the world's land mass is about 37 billion acres (the USA has 2.24 billion acres), much of which is permanently frozen. Clearly it is impossible to accomodate the world's energy needs if one depends *only* on bio-mass. However with the aid of nuclear electricity which can run alcohol distillation plants, fertilizer production, and the manufacture of farm equipment, four times less land is needed and "only" one-third of the USA's lands

(0.6 billion acres) is needed. In this case, bio-alcohol can be viewed as a synfuel produced from nuclear electricity and sunshine as prime energy sources. Under that scenario, non-portable nuclear energy is converted into portable energy and the 80% to 90% energy penalty for harvesting and extraction is not critical. Globally, assuming 40% of total energy consumption requires portable fuels, one would need a formidable 2.4 billion acres or 30% of the world's arable lands. Only in countries like the USA and Brazil with vast fertile land areas can such bio-fuel production be sustained, *provided sufficient nuclear electricity is also available*. Although bio-fuels like alcohol emit globe-warming carbon-dioxide upon combustion, there is no net addition of this gas to the environment since plants take up carbon-dioxide to make extractable carbon-based bio-fuels.

Solar cells converting sunshine directly into electricity, have been under subsidized development for more than 50 years. The best units have overall efficiencies of about 8% (including losses from voltage up-conversions and storage), yielding about 437 kW per acre of solar panels when sun-shine peaks. Allowance for diurnal, seasonal, and weather fluctuations reduces this value by 75% to an average 109 kW per acre, while a further reduction of 25% of land area for access roads to install and maintain solar panels, storage batteries, and transmission lines, yields a final 82 kW per acre. To replace all present petro-fuel and electric energy generation with solar-cell energy requires (9.1 billion kW)/(82 kW/acre) = 111 million acres of sunny open land. Construction of a large solar complex generating a million kW of electricity costs about \$ 10,000 per kW and requires 12,500 acres of desert land. To provide 9.1 billion kW world-wide by solar cells then requires \$ 91 trillion of capital investment and 111 million acres of accessible desert. Should all future homes possess solar panels to provide self-sufficient domestic power (30% of total energy pie), \$30 trillion might be passed on from the utilities to home-owners, who probably will pay double this amount (\$ 60 trillion). Utilities must still invest \$ 61 trillion in this case.

The economics of windfarms is also fraught with location restrictions and large-area problems. Assuming these problems are solvable, wind-power is estimated to require an investment of \$64 trillion to deliver 9.1 billion kW to the world. This assumes 1,250,000 advanced 2 MW(e) wind turbines together with power distribution systems and modern electric storage capacitors when winds are not blowing hard enough (80% of the time). In contrast, to supply the world's electricity needs and replace all petro-fuels with synfuels produced with nuclear heat or electricity from reactors that generate 1 million kW each, requires (9.1 billion kW)/(1 million kW) = 9,100 nuclear reactors world-wide. Real estate for 9,100 reactors comes to 364,000 acres, assuming each reactor takes 40 acres for buildings and cooling towers. They can be built anywhere away from earthquake faults. At \$1.8 billion each, the 9,100 reactors would demand \$ 16.4 trillion of capital. It is not difficult to guess what utilities and capital investors prefer when choosing between \$ 91 trillion for solar, \$ 64 trillion for wind, or \$ 16 trillion for the nuclear option.

For the USA, replacement of primary oil and coal requires an investment of \$35 trillion for solar, \$25 trillion for wind, and \$6 trillion for nuclear power.

Besides these capital cost disincentives, the enormous land areas needed for solar and wind energy cause a disturbance of local ecologies and will spoil many scenic landscapes. Exclusive use of these sources for prime energy would make them very unpopular with environmentalists. Aside from capital costs, one must consider maintenance costs. Solar cells require constant cleaning to remove dust or bird droppings, and must be replaced every ten to twenty years due to erosion and deterioration (sand storms, etc). They are made of gallium-arsenide or copper-indium-diselenide, requiring toxic silanes, arsenic, etc. for their manufacture. Toxic wastes generated in producing solar cells for global use, dwarf the amount of nuclear fuel and waste for the nuclear option. For wind-power generation, the mechanical maintenance of thousands of turbines and protective measures to avoid killing thousands of birds, seriously effects its economics. The secret of controlled nuclear power is that it is a thousand times more concentrated than any non-nuclear method.

3.4. A BRIEF HISTORY OF ENERGY

In 1650, the world was populated by 550 million people, or less than 10% of the present population. Besides sunshine which energizes agriculture, controllable energy resources available to man were:

Human Labor (via contracts, indenture, slavery, or prisoners to build structures, roads, etc).

Animal Labor (horses, donkeys, camels, elephants, dogs, for transporting people and goods).

Wood, Oils, and Coal (burned for lighting, cooking, heating, melting/forging copper and iron).

Wind (windmills grinding wheat, pumping water; sailing ships transporting goods and people).

Water Flow (waterwheels grinding wheat, aquaducts, drainages, etc).

These main forms of energy were all utilized in one way or another to satisfy man's basic needs and wants for water, food, warmth (heat), housing; or for manufacture of goods such as clothes, candles, furniture, saddles, carriages, ships, armor, weapons (for hunting, defense, and warfare), etc; or for moving people and goods (transportation). They are still available, but now we have 6 billion people.

In the 18th, 19th, and early 20th century, several discoveries and inventions were made that profoundly changed the world's energy picture. First came the steam engine, originally demonstrated by James Watt of Scotland in 1770. It burned coal that heated water in a boiler, converting it into steam which in turn pushed pistons that turned wheels. It was actually preceded by an 'atmospheric pump' that used condensing steam to pull a vacuum for suction, invented in 1712 by Englishman Thomas Newcomen, to pump water out of flooded mines. However it was not until 1807, after engineer Robert Fulton (USA) made improvements in the mechanical linkages and conversion cycle of heat to mechanical motion, that steam-ships and steam-locomotives were developed worldwide. Starting in the 1820's,

steamships plowed the oceans and big rivers of the world, while trains pulled by steam-locomotives traveled over railroad networks all over the globe, connecting widely separated land-locked territories. Coal became a very important commodity and many new coal mines were opened to feed the hungry steam engines of the 1800's. Some coal-fueled steam-powered automobiles were also built, but only the rich could afford them.

Between 1878 and 1885, pioneers Elihu Thomson and Nikola Tesla learned to generate alternating current (AC) electricity in a continuous fashion, and subsequently invented the AC electric induction motor, electric lightbulbs, and many other products run by electric power. Because AC voltages are much easier converted and boosted, AC power distribution over copper wires is far less lossy than Thomas Edison's DC (= direct current) electricity that powered the street-lights of New York in the 1890's. AC electricity can be delivered fairly efficiently over large distances. George Westinghouse who supported and financed Tesla's work, built and exhibited the first commercial hydroelectric turbo-generator at the 1893 World Fair in Chicago and shortly thereafter completed the first large hydroelectric plant powered by waterfall-driven turbines at Niagara Falls in 1895. It delivered a 'whopping' 1.1 MW(e) of electric power that ran the lights and streetcars of Buffalo, NY, twenty-six miles away. General Electric built the first power lines for this venture. Invention of the coal-burning steam-driven turbine in 1884 by Sir Charles Parsons in England, provided an alternative to the waterfall-driven turbines used in hydroelectric power plants. In Parson's scheme, a boiler heated by burning coal converts water to pressurized steam which in turn drives a turbine that generates electricity. Steam turbines are now the major generators of electricity, and coal is the prime energy source for 52% of all electric power generation in the USA. Only 5% comes from hydro-electric sources, since most rivers in the USA suitable for dams and large-scale electric power generation have been exhausted. Additional steam-turbine electricity is presently generated by heat from uranium fission (21%), and by burning natural gas (12%), petroleum/oil (3%), or industrial waste (wood, biomass, alcohol) (5%). Geothermal steam, wind-power, and solar-cells provide the remaining 2%.

Two additional world-changing developments were the introduction of the petrol-fueled internal combustion engine for automobiles in 1889 made by Gottfried Daimler in Germany, and the flight of a petrol-engine-powered airplane in 1904 by Orville and Wilbur Wright. Mass-production of autos in 1908 by Henry Ford in the USA, and selling his cars on the installment plan, were another two revolutionary steps that changed the world. After 1908, mass-produced petrol-powered cars overtook steam automobiles and horse-drawn carriages, while most coal-burning locomotive and steamship engines were replaced by diesel engines. The rapid expansion of automobile usage and aviation, with increased demands for oil-derived petrol and diesel, created the large oil companies of today which recover, refine, and distribute enormous quantities of refined oil for a worldwide market.

In the Middle East, underground sources of oil were known to exist for centuries and exploited to provide fuel for oil-burning lamps and stoves. When it appeared

that oil could power automobiles, William D'Arcey, an Australian businessman, obtained a sixty-year concession in 1901 to drill and extract oil from 500,000 square miles or five-sixths of what is now Iran [Ref. 12]. He formed the Anglo-Persian Oil Co, later to become Anglo-Iranian and still later British Petroleum (BP). Similarly, in 1904 in what is now Iraq, the Armenian C.S. Gulbenkian recognized the enormous potential of oil and persuaded the Turkish Sultan Abdul Hamid to transfer ownership of immense tracts of land from the Ministry of Mines to private ownership (mostly himself), establishing the Iraq Petroleum Co. Later on, BP and Royal Dutch Shell obtained contracts to exploit the oil fields in Iran, Iraq, and Arabia and to export the oil. U.S. companies Exxon and Mobil, which had their starts in the oil fields of Texas and California, entered the Middle East arena in 1928, when they became part owners of the Iraq Petroleum Company. Gulf, Standard Oil of California (Chevron), and Texaco got involved somewhat later. Control over the Middle East oil fields stayed firmly in the hands of these 'seven sisters' until 1973, when host governments demanded more control and revenue from their mineral wealth. Today the oil-producing nations of the world have united under OPEC (Organization of Petroleum Exporting Countries) which regulates the world's oil production rates and prices.

In summary, two energy sources already known in the middle ages but previously consumed in modest amounts, were suddenly catapulted into major world commodities, namely:

Coal – experiencing a large increase in demand after 1820 to empower steam engines; and after 1900 to vaporize water for electricity-generating steam turbines.

Oil – experiencing large-scale exploitation after 1901 to fuel automobile combustion engines.

Today's oil consumption continues to rise, driven by ever expanding fleets of petrol-burning transport vehicles and craft, while the continuously expanding use of coal is due to increasing demands for electricity. Oil has allowed mankind to transport goods and people locally as well as to any part of the world quickly at an affordable cost, while electric power has enabled man to develop numerous new manufacturing techniques, products, and services. Electricity is providing modern homes with light, heat, air conditioning, electric stoves, refigerators, radios, televisions, telephone service, etc.

Increased use and availability of oil and coal has also promoted world population growth and a desire in the less developed countries to acquire modern comforts. Oil and coal consumption rates have thereby reached a level where depletion of oil is forecast to occur in a few decades (one generation), while coal is expected to last only one century if world demand continues to rise at the present rate.

Without oil, it is impossible to maintain current forms of transportation, and without trucks and airplanes it is not feasible to produce and distribute enough food to feed six billion people presently on our planet. Fortunately, nuclear fission was discovered in 1939, and sufficient extractable uranium and thorium has been found on earth to generate all the needed electricity for manufacturing portable fuels for

the entire world for the next 1,500 years. It appears that divine intervention wanted man to discover this new energy source in time to avert a human catastrophe when oil runs out.

The history of the discovery of uranium fission is a very interesting one and worthy of elaboration. Most of the following information is from Richard Rhodes' fascinating book [Ref. 11]. In Italy in the mid-1930's, Enrico Fermi was bombarding uranium with newly discovered neutrons, and observed that neutrons (atomic mass $M = 1$) were absorbed by uranium (atomic mass $M = 238$), causing the latter to transmute into new product elements with different atomic mass. Based on previous research, he believed that the atomic masses of the new transmuted elements had to either gain 1 atomic mass unit or loose 1 or 4 units from the original atomic mass $M = 238$ of uranium[7]. But he found that some product atoms did not have any of the expected chemical properties for a species with say $M = 239$ and $Z = 92$. In Dahlem, Germany, at the Kaiser Wilhelm Institute (KWI), Otto Hahn, Lise Meitner, and student Fritz Strassman decided to redo Fermi's measurements. They also found products with $M = 144$ and $Z = 56$, disagreeing with prevailing theory that they should not differ by more than a few units from $M = 238$ and $Z = 92$.

While Hahn and Meitner were pondering this result, Hitler invaded Austria in 1938 and incorporated it into Germany. Lise Meitner who was Austrian, was faced with new ugly Nazi laws that suddenly applied to her. She learned that her government-funded contract with KWI was about to be canceled because she was part Jewish, in spite of pleas by her colleagues. With the help of a Dutch physicist (Dirk Coster) who picked her up in Dahlem, she fled Germany and went on a train to Holland. From there she went to Niels Bohr's institute in Copenhagen, Denmark for a brief rest before going on to Stockholm, Sweden to work with Karl Siegbahn. In December 1938, Meitner got a letter from Hahn telling her he had repeated the experiments with neutron bombardments of uranium, and after careful chemical analysis of the products, he and Strassman found one product was definitely the element barium with $Z = 56$, *not at all* close to $Z = 92$. Did she have any ideas how to explain that?

Meitner met with her nephew Otto Frisch during Christmas 1938 in Sweden, and discussed Hahn's letter with him. After expressing skepticism but still preoccupied with Hahn's observation of barium, Meitner suddenly remembered a statement by Niels Bohr that he believed the nucleus of an atom such as uranium was like a pulsating liquid drop. They then conceived of the possibility that a nucleus could split

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[7] A nucleus is made up of Z protons and M - Z neutrons. Each of the Z protons have unit atomic mass and unit charge. They determine the total positive charge of a nucleus, hence Z is also called the atomic charge number. The mass of a neutron is almost the same as the mass of a proton, but it has no electric charge. The total number M of 'nucleons' is the sum of protons and neutrons in a nucleus and is called the atomic mass number of a nucleus. A given element has a fixed number of protons Z, but can have different 'isotopes' with different numbers of neutrons and thus different mass number M. The most abundant uranium isotope is U-238 with $M = 238$ and $Z = 92$, i.e. 92 protons and 146 neutrons, while fissionable U-235 has 92 protons and 143 neutrons.

in two halves during a drop-stretching waist-producing pulsation after absorption of a neutron. They estimated this could happen if the atomic charge number exceeded Z $\approx$ 100 because of repulsion between the two halves, each half being filled with many positively charged protons. Uranium with Z = 92 protons, was close to this value. The two 'fission' products should each have atomic charge numbers whose sum was close to 92. That is if barium with $Z_1 = 56$ was one product, the charge number of the other fission product had to be near $Z_2 = 36$ if protons were to be conserved. Fissioning uranium actually yields product atoms with Z_1 and Z_2 spread over a range of values rather than one particular set. But the proton sum $Z_1 + Z_2 \approx 92$ does hold. Additional calculations convinced Meitner and Frisch that their hypothesis was physically quite plausible. They also determined that the liberated energy had to be enormous: ~ 200 Mev per fission or 82 GJ per gm of $U - 235 \approx 1$ MW-day per gm U-235 (~ 40 tankfulls of petrol per gm U-235!).

Frisch who worked at Bohr's institute in Copenhagen returned to Denmark right after the Christmas 1938 visit with his aunt in Sweden. He told Niels Bohr what he and Lise Meitner had deduced from the data of Hahn and Strassman. Bohr himself had proposed the liquid-drop model for a nucleus, and immediately concurred with their conclusion, stating this was an important discovery. Next, Frisch put together an experiment using an ion chamber he had in his lab. On January 13, 1939 he found that the masses M of some products from neutron-bombarded uranium atoms detected by the chamber, were much larger than the usually observed protons (M = 1, Z = 1) or helium ions (M = 4, Z = 2). Indeed they had values of about half the mass of a uranium atom (M = 238). This was experimental proof that neutron-bombarded uranium can fission. Niels Bohr left by boat to lecture at Princeton, USA, where he informed his colleagues about the Meitner-Frisch findings on January 17, 1939, after receiving a telegram from Meitner. One of these colleagues was Enrico Fermi who had just arrived in New York on January 2, 1939 after returning from Stockholm where he had received the Nobel prize for his pioneering work with neutrons. Fermi had decided not to return to fascist Italy under Mussolini, because his wife was Jewish and faced persecution.

The splitting uranium story told by Bohr was quickly passed around by the small U.S.'nuclear club'. Within a week, experiments with ion chambers were conducted at the National Bureau of Standards, which confirmed the observations by Frisch. Shortly thereafter, Einstein wrote a letter to president Roosevelt warning him Hitler might develop a super weapon using uranium fission. Thence the secret US Manhattan Project was born. To prove that uranium fission could work on a macroscopic scale, Fermi designed and built the first nuclear reactor at the University of Chicago, which went 'critical' on December 2, 1942. Next, in an incredibly short two years, plutonium production reactors were erected at Hanford, Washington, and a gigantic gaseous diffusion plant was built at Oak Ridge, Tennesee, to separate fissionable U-235 isotopes from natural uranium (0.7% U-235, 99.3% U-238). At Los Alamos, New Mexico, a team of the brightest scientists in the world under the leadership of Robert Oppenheimer worked feverishly to develop a nuclear bomb, thinking Hitler might be ahead of them. After testing the first bomb at Alamogordo,

N.M. on July 16, 1945, WW-II was ended with the detonation of two additional nuclear weapons, one on August 6, 1945 at Hiroshima, and the other on August 9, 1945 at Nagasaki, Japan. The irony is, that the three fascist-ruled nations who had banded together to conquer the world, were ultimately defeated by an international group of superb scientists, many of whom, like Lise Meitner and Enrico Fermi, had been driven out of their countries because Hitler alleged they or their family members were ethnically inferior!

After WW-II ended in 1945, vigorous development of nuclear *power reactors* (not to be confused with weapons!) occurred worldwide for the purpose of generating electric power by converting fission heat $\rightarrow$ steam $\rightarrow$ electricity. Today uranium produces 21% of all electricity in the USA, 85% of all electric power in France, and close to 50% of all electric power in Japan. Other countries (e.g. China) are quickly following. Clearly the latest, and today's most valuable energy resource is:

Uranium (starting around 1950)

Aside from electricity, 'research' reactors can produce special 'radioisotopes' used in thousands of hospitals by physicians specialized in nuclear medicine. The radioisotopes are tagged onto special pharmaceutical agents used for diagnostics or therapeutic cancer-fighting applications. Radioisotope-tagged molecules are also used widely as tracers in biotechnology and pharmaceutical research, revealing biological processes and the effects of experimental drugs in the human body. Finally, about two-thirds of reactor heat which is rejected at the lower temperature in electricity-generating steam cycles (see footnote 3), can be used for desalinization of seawater (California) or for mass urban heating (Mongolia).

3.5. SUMMARY OF PRIMARY ENERGY SOURCES

Natural prime energy sources are either 'renewable' or 'non-renewable'. Non-renewables are extracted from the earth with energy expenditures that are a fraction ($\sim$ 20% or less) of the potential heat of combustion of the energy source. However because there is only a finite supply, they are depletable, i.e. non-renewable. Renewable energy resources on the other hand are assumed to be always available. Thus one has:

(a) Non-Renewable Sources:

(1) Fossil Fuels: Oil, Natural Gas, Coal
(2) Nuclear Fuels: Uranium, Deuterium
(3) Geothermal Energy: Heat Pockets

(b) Renewable Sources:

(4) Water Falls and Tidal Waves (Hydro Energy)
(5) Sunshine (Solar Energy)
(6) Wind Energy

Of energy sources (1) through (6), only item (1), oil, natural gas, or coal, are portable and can be taken along in an automobile, truck, or airplane to power it. Refined oil yields portable petrol (hydrocarbon mixtures rich in octane (C_8H_{18})), and portable diesel (crude oil distillates with higher boiling point) which are liquid at room temperature. Natural gas (natgas) contains mostly methane (CH_4) but also fractions of ethane, propane, butane (C_2H_6, C_3H_8, C_4H_{10}). As mentioned, compressed at $\sim$120 atm in portable high-pressure tanks, natgas has fueled car engines. Coal can of course be carried along and burnt to make steam that powers a steam engine as was done in the 1800's. Today most coal and natgas resources are burned in power plants to provide steam heat that generates electricity via a turbine.

Regarding item (2), nuclear powered ships and submarines have been built and nuclear rockets or aircraft are feasible, but it is not practical nor safe for automobiles to carry nuclear reactors under the hood. Nuclear fission power to propel aircraft and rockets has not been implemented because of problems arising in potential crashes. Electric-grid energy, whether produced by uranium, coal, or other means, is clearly not in a portable form that can be carried by surface vehicles or aircraft as a replacement for petrol, when oil and gas are gone. However electric-grid energy can be converted into portable synfuel energy, as discussed in the next section. In large cities and parts of Europe, electric trains have been developed that use (nuclear) electric energy from the power grid by means of sliding blades that contact high-voltage bare overhead wires or ground-level trenched conductors.

In the 1980's, geothermal steam ran a power plant near some geysers in Cobb, Northern California. But steam pressure was gradually lost and the plant was shut down after six years. Such reservoirs of steam are evidently exhaustible like oil. Better geothermal schemes are being explored in France, Japan, and Australia. In the Cooper Basin of Queensland, Australia, anomalously hot underground fractured rock formations of about one thousand km^3 have been found at a depth of 3 to 4 km. Water under pressure ($\sim$ 600 atm) is piped into these dry heat pockets or 'hot-beds' and pressurized hot water at $T \approx 250°C$ is extracted and returned to the earth surface where its heat is exchanged with a second loop that converts a low-boiling-point fluid into vapor which in turn drives a set of vapor turbines to generate electric power [Ref 47]. Water is continuously resupplied to the underground hot-bed at the same rate as it is removed. The scheme is similar to a nuclear Pressurized Water Reactor (Chapter 5) in which fissioning uranium heats circulating water pressurized at $\sim$150 atm to $\sim$ 280°C, whose heat is transferred to a secondary low-pressure water loop that produces steam for generating electricity. The Australian underground hot-beds are estimated to hold sufficient quantities of extractable heat ($\sim$160 millionGJ/km^3) to run thirty 1000 MW(e) electric power plants for 30 years. Eventually they will be exhausted, so we listed geothermal hot-bed energy as item (3) under non-renewable primary energy sources.

One might think that heat from the earth's interior core and mantle could replenish the heat removed from underground hot-beds, but thermal conduction through solid rock is too slow to allow this. Without thermal insulation by rocks, most of the

earth's interior heat would have leaked out long ago. Occasional volcanic eruptions are the only outlets of heat from below the earth's mantle. Hot-beds are different. They are puddles of silicate melts which during the earth's creation came to rest within the earth crust at depths of 3 to 10 km from the surface. After the earth cooled, the silicate puddles became fractured rock but remained hot in areas where covering rock is highly insulating [Ref 47].

Renewable item (4), hydro-power, is derived from the kinetic energy stored in bodies of water (lakes and rivers) that move due to earth gravity forces. It is used in hydro-electric plants where the flow of river water or a water-fall is passed through hydro-electric turbines that generate electric power. There is no direct application of hydro-power to provide portable propulsion for land vehicles, except for river-craft that move downstream with the river flow. Today most rivers with suitable conditions to generate hydro-electric power have been dammed, and new river sources are essentially exhausted. Tidal wave energy is re-examined now and then but seems only marginally worthwhile to exploit.

The harvesting of renewable solar and wind energy is primarily useful in remote locations that need electric power. Assuming wind is available, wind turbines can provide 1 to 2 MW(e) peak power per turbine at an installation cost of $ 1 million/MW(e). Solar power may be useful in desert regions, but installation and maintenance costs of solar stations are still high even though prices of solar cell arrays have come down considerably in the last twenty years. Of course winds are not always blowing and the sun is not always shining, which limits the use of solar and wind energy in many parts of the world. To replace petro-fuels with solar and wind energy on a global scale was reviewed in Subchapter 3.3.

For transportation applications, wind-powered sailing ships have of course been used for millenia, while sail-driven or solar-cell-powered cars have been built and do exist. Today these are great for sports but they could not replace the combustion engine to run bulldozers, trucks, cars, or any mass transportation vehicles. One finds in general that solar and wind energy, while attractive, lack sufficient power density to compete with modern compact high-power engines and fuels, and with nuclear power generation. High-density power generation lowers capital equipment costs immensely compared to costs of large-foot-print systems that collect and concentrate solar energy for example.

Conversion of biomass or organic wastes into energy-carrying synfuels by fermentation, digestion, and other techniques is only economically feasible if the required processing energy is supplied by (nuclear) electricity or heat. As mentioned, in this case extraction of a biofuel (e.g. alcohol or fat) from biomass represents a synfuel whose inherent locked-up energy is made available for combustion due to the input of externally provided (nuclear) electric/heat energy for plant cultivation and biofuel extraction. Non-portable electricity or heat energy is thus essentially converted into portable fuel energy in this case. To replace all present usage of petrol with biofuels, it was shown in Subchapter 3.3 that besides the availability of (nuclear) electricity or heat, about one-third of all available land in the world would have to be used for farming bio-fuel producing plants. This is feasible only in

countries with vast thinly populated fertile lands such as Brazil or the USA, but may be impossible for densely populated Western Europe. If one dictates that no coal or uranium can be used to generate primary electricity, and only bio-fuel production is allowed, one finds that one needs four times all arable land in the world to replace present petrofuel energy. Clearly this is an untenable proposition.